

Reduced-Complexity Decoder of Long Reed-Solomon Codes Based on Composite Cyclotomic Fourier Transforms

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Abstract—Long Reed-Solomon (RS) codes are desirable for digital communication and storage systems due to their improved error performance, but the high computational complexity of their decoders is a key obstacle to their adoption in practice. As discrete Fourier transforms (DFTs) can evaluate a polynomial at multiple points, efficient DFT algorithms are promising in reducing the computational complexities of syndrome based decoders for long RS codes. In this paper, we first propose partial composite cyclotomic Fourier transforms (CCFTs) and then devise syndrome based decoders for long RS codes over large finite fields based on partial CCFTs. The new decoders based on partial CCFTs achieve a significant saving of computational complexities for long RS codes. Since partial CCFTs have modular and regular structures, the new decoders are suitable for hardware implementations. To further verify and demonstrate the advantages of partial CCFTs, we implement in hardware the syndrome computation block for a $(2720, 2550)$ shortened RS code over $\text{GF}(2^{12})$. In comparison to previous results based on Horner's rule, our hardware implementation not only has a smaller gate count, but also achieves much higher throughputs.

I. INTRODUCTION

Since syndrome-based hard-decision decoders of Reed-Solomon (RS) codes [1] have quadratic complexities in their code lengths, RS codes of short and medium lengths have widespread applications in modern digital communication and storage systems. To meet ever higher demand on error performance, long RS codes (or shortened RS codes [2], [3]) over large finite fields have been considered in theoretical studies. For example, RS codes with thousands of symbols over $\text{GF}(2^{12})$ are considered in optical communication systems [2] and magnetic recording systems [4], [5] to achieve low bit error rates. One of the key obstacles to the adoption of such long RS codes in practice is high complexity caused by their extreme code lengths as well as the large sizes of their underlying fields.

Fast algorithms for discrete Fourier transforms (DFTs) over finite fields are promising techniques to overcome this obstacle. This is because all steps except the key equation solver in syndrome-based hard-decision RS decoders [1] — syndrome computation, Chien search, and error magnitude evaluation — are polynomial evaluations. Hence, they can be formulated as DFTs over finite fields.

Recently, cyclotomic fast Fourier transforms (CFFT) over finite fields have been used to reduce the complexities of RS decoders [6], [7]. CFFTs proposed in [6], [8], [9] have low multiplicative complexities, but they have very high additive complexities. By using techniques such as the common sub-expression elimination (CSE) algorithm in [10], the additive

complexities of CFFTs can be significantly reduced, leading to small overall computational complexities for DFTs with lengths up to 1024 [10]. By treating syndrome computation, Chien search, and error magnitude evaluation as partial CFFTs or dual partial CFFTs, the overall computational complexities of these steps can be significantly reduced for short and medium RS codes [6], [7]. Unfortunately, this approach will not be feasible for long DFTs and hence long RS codes. This is because the CSE algorithm itself has a prohibitively high computational complexity when applied to long DFTs. Without the CSE algorithm, the overall computational complexities of CFFTs will be higher than other approaches due to their additive complexities.

In this paper, we devise reduced-complexity decoders for long RS codes based on composite cyclotomic Fourier transforms (CCFTs) [11]. CCFTs first decompose long DFTs with composite lengths into short sub-DFTs via the prime-factor algorithm [12] or the Cooley-Tukey algorithm [13], and then implement the sub-DFTs with CFFTs. We remark that CFFTs are special cases of CCFTs corresponding to trivial decompositions. The decomposition leads to significantly reduced additive complexities at the expense of multiplicative complexities, resulting in lower overall computational complexities than CFFTs for moderate to long DFTs in practice [11]. Furthermore, the decomposition also endows CCFTs with modular structures, which are suitable for hardware implementations.

The main contributions of this paper are as follows:

- We first propose partial CCFTs and then apply them to implement syndrome computation, Chien search, and error magnitude evaluation of RS decoders. Partial CCFTs not only inherit the two advantages (lower additive complexities and modular structures) of full CCFTs, their two-tier structure is also suitable for the implementation of decoders for shortened RS codes. For instance, for DFTs in shortened RS codes, certain time-domain elements are zeros and certain frequency-domain components are not needed. For partial CFFT, either property can lead to multiplicative complexity reduction but not both at the same time. The two-tier structure of CCFT, however, enables us take advantage of both properties simultaneously to reduce the multiplicative complexity. Consequently, our results show that partial CCFTs leads to a significant saving of computational complexities for long RS codes.
- To further verify and demonstrate the advantages of partial CCFTs, we implement in hardware the syndrome

computation block for a (2720, 2550) shortened RS code over $\text{GF}(2^{12})$. In comparison to previous results based on Horner's rule, our hardware implementation not only has a smaller gate count, but also achieves much higher throughputs.

The rest of this paper is organized as follows. We review CCFTs and CCFTs in Sec. II. Sec. III first proposes partial CCFTs and then presents RS decoders based CCFTs. The hardware implementation results are provided in Sec. IV. Finally, our paper concludes in Sec. V.

II. BACKGROUND

A. CFFTs and CCFTs over Finite Fields

Assuming that $\alpha \in \text{GF}(2^m)$ is an element of order n , the DFT of an n -dimensional vector $\mathbf{f} = (f_0, f_1, \dots, f_{n-1})^T$ over $\text{GF}(2^m)$ is given by $\mathbf{F} = (f(\alpha^0), f(\alpha^1), \dots, f(\alpha^{n-1}))^T$, where $f(x) = \sum_{i=0}^{n-1} f_i x^i$. That is, DFTs can be viewed as polynomial evaluations. The vector \mathbf{f} is said to be in the time domain and \mathbf{F} in the frequency domain. Direct CFFTs (DCFFTs) [8] formulate the DFTs as $\mathbf{F} = \mathbf{A}\mathbf{L}\mathbf{f}'$, where \mathbf{A} is an $n \times n$ binary matrix, \mathbf{L} a block diagonal matrix with each block cyclic, and \mathbf{f}' a permutation of \mathbf{f} . Since the multiplication between a cyclic matrix and a vector can be done by efficient bilinear algorithm of cyclic convolution, CFFTs can be computed by $\mathbf{F} = \mathbf{A}\mathbf{Q}(\mathbf{c} \cdot \mathbf{P}\mathbf{f})$, where \mathbf{Q} and \mathbf{P} are binary matrices, \mathbf{c} is a pre-computed vector, and \cdot denotes an entry-wise multiplication between two vectors. Two variants of DCFFTs, referred to as inverse CFFTs (ICFFTs) [6] and symmetric CFFTs (SCFFTs) [9], respectively, compute the DFTs by $\mathbf{F} = \mathbf{L}^{-1}\mathbf{A}^{-1}\mathbf{f}'$ and $\mathbf{F} = \mathbf{L}^T\mathbf{A}^T\mathbf{f}'$, respectively. Since it has been shown that ICFFTs and SCFFTs are equivalent [10], without loss of generalization we consider only DCFFTs and SCFFTs in this paper.

The composite cyclotomic Fourier transform in [11] can further reduce the overall computational complexity by decomposing the long DFTs into short sub-DFTs via the prime-factor algorithm [12] or the Cooley-Tukey algorithm [13]. The decompositions of the DFTs reduce the additive computational complexity directly. Moreover, because of the short length of the sub-DFTs, sophisticated tools such as the CSE algorithm in [10], can be readily used to reduce the additive complexities of CCFTs. CCFTs also have a modular structure, which is desirable in hardware implementation. The sub-DFTs can be used as sub-modules, which can be reused to save chip area or parallelized to increase the throughput.

B. Reed-Solomon Decoders based on CFFTs

Henceforth in this paper, we focus on cyclic Reed-Solomon (RS) codes, which can be decoded by syndrome-based decoders considered herein [1]. For an (n, k) cyclic RS code over $\text{GF}(2^m)$ with $n|2^m - 1$ and $n - k = 2t$, it can correct up to t errors or $2t$ erasures. An (n', k') shortened RS code can be viewed as a sub-code of an (n, k) RS code where the symbols at the position $i \geq n'$ are always zero. For a received vector $\mathbf{r} = (r_0, r_1, \dots, r_{n-1})^T$, the syndrome-based errors-only (errors-and-erasures, respectively) decoder of RS codes in the time domain consists of the following three steps [1]:

- 1) Compute the $2t$ syndromes $s_j = \sum_{i=0}^{n-1} r_i \alpha^{ij}$ for $0 \leq j \leq 2t - 1$, where α is an n -th primitive element.
- 2) Compute the error (errata) locator polynomial $\Lambda(x)$ and error (errata) evaluator polynomial $\Omega(x)$ by the Berlekamp-Massey algorithm (BMA) or the extended Euclidean algorithm.
- 3) Find the error (errata) positions by the Chien search. That is, the error positions are obtained by finding the root of $\Lambda(x)$. Find the error (errata) value by Forney's formula, which evaluates $\Omega(x)$ and $\Lambda'(x)$ (formal derivative of $\Lambda(x)$) at the error (errata) positions.

Since evaluating a polynomial at multiple points can be implemented as a DFT, DFTs can be used to reduce the computational complexity of steps 1 and 3. When DFTs are used to implement syndrome computation in the RS decoder, only $2t$ frequency-domain elements are needed. Hence, the unnecessary rows and columns of the matrices in DCFFTs or SCFFTs can be removed to reduce both multiplicative and additive complexities, resulting in partial DCFFTs and partial SCFFTs. Similarly, when DFTs are used to evaluate the error (errata) locator and evaluator polynomials, many time-domain elements are zeroes due to the limited degrees of both polynomials. Again the unnecessary rows and columns of the matrices in DCFFTs and SCFFTs can be removed, leading to dual partial DCFFTs and dual partial SCFFTs. Since a shortened RS code is essentially a RS code with zero symbols, these zero symbols are treated as zero time-domain elements. When DFTs are used to implement syndrome computation, the Chien search, and Forney's formula, these DFTs are partial in both time and frequency domains.

Although the complexity of the Berlekamp-Massey algorithm is important to efficient RS decoders, the implementation of the Berlekamp-Massey algorithm is not considered henceforth in this paper, since the computational complexity of the Berlekamp-Massey algorithm cannot be reduced by DFTs.

III. RS DECODERS BASED ON PARTIAL COMPOSITE CYCLOTOMIC FOURIER TRANSFORMS

In this section, we first propose partial CCFTs and then devise syndrome-based time-domain RS decoder based on our partial CCFTs. The complexities of our RS decoder are compared with previous works in the literature.

A. Partial Composite Cyclotomic Fourier Transforms

When $N = N_1 N_2$, with the prime-factor algorithm [12] or the Cooley-Tukey algorithm [13], an N -point CCFT can be carried out in a two-tier structure. The first tier performs N_2 N_1 -point CFFTs and the second performs N_1 N_2 -point CFFTs. When the greatest common divisor of N_1 and N_2 is greater than one, twiddle factors are needed. When N_1 and N_2 are co-prime to each other, no twiddle factor is required. When N_1 or N_2 is composite, N_1 - or N_2 -point DFTs can be further decomposed, leading to multi-tier structure. Fig. 1 shows the two-tier structure of a 3×5 CCFT, where the first tier consists of five 3-point CFFTs and the second tier three 5-point CFFTs. This regular and modular structure is suitable for hardware implementations, since it is much easier to apply

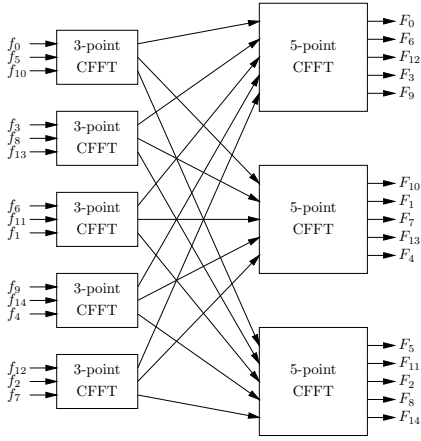


Fig. 1. The regular and modular structure of our 15-point CCFT based on a 3×5 decomposition.

architectural techniques such as folding and pipelining to this regular and modular structure, leading to efficient hardware implementations.

When some frequency-domain components are not needed or some of the time-domain elements are always zeroes, the corresponding rows and columns of matrices in the sub-CFFTs can be removed, resulting in partial CCFTs. As shown in [11], CCFTs have lower computational complexities than CFFTs in evaluating long DFTs, and hence we expect that partial CCFTs have advantages in reducing the computational complexities of decoders for long RS codes.

We remark that if we decompose an N -point DFT as $1 \times N$, the corresponding partial CCFT will reduce to partial SCFFT, and if we decompose the DFT as $N \times 1$, the corresponding partial CCFT will reduce to partial DCFFT. Therefore, our partial CCFTs include partial DCFFTs and partial SCFFTs as special cases. In this sense, DFT decomposition provides another degree of freedom to reduce the computational complexities of DFTs. In the following, we focus on the computational complexities of partial CCFTs with non-trivial decompositions, i.e., decompositions other than $1 \times N$ and $N \times 1$.

We discuss the complexity of partial CCFTs can be reduced based on partial time or frequency domain elements, and compare partial CCFTs with partial CFFTs. Assuming a two-tier structure for simplicity, there are three possible scenarios:

1) **When limited frequency domain elements are needed.**

For RS codes, when DFTs are used to compute the syndromes of a received vector, only the first $2t$ frequency-domain components are needed. The results in [7] show that the multiplicative complexity of a partial SCFFT is reduced greatly, but because the matrix \mathbf{A} is not sparse, it is hard to reduce the multiplicative complexity of a partial DCFFT. Even though partial DCFFTs have smaller additive complexities than partial SCFFTs, they have higher overall computational complexities. For partial CCFTs, the multiplicative complexity of the second tier can be directly reduced due to the unnecessary frequency-domain components. However, since computing even one frequency-domain component of an N_2 -point vector

requires all of the time-domain elements, the outputs of the DFTs in the first tier may only have unnecessary frequency-domain components in some rare cases, e.g., the number of the DFTs in the second tier is more than that of the necessary frequency-domain components, and hence the complexity of the DFTs in the first tier cannot be reduced in most cases. Thus, the complexity reduction of partial CCFTs is not as great as partial CFFTs.

2) **When some time domain elements are zero.**

For RS codes, when DFTs are used to reduce the computational complexities of Chien search and error evaluation, only a few time domain components are non-zero, and hence partial DCFFTs can reduce the multiplicative complexities greatly and have lower overall complexities. For partial CCFTs, the multiplicative complexity of the first tier can be directly reduced due to the zero time domain components, while the complexity of the second tier cannot be easily reduced unless in rare cases.

3) **When limited frequency domain elements are needed and some time domain elements are zero.**

For shortened RS codes, only part of the time-domain elements are nonzero and only part of the frequency-domain components are needed. Neither partial DCFFTs nor partial SCFFTs can take full advantage of both properties simultaneously. In contrast, the two-tier structure of partial CCFTs is advantageous. Due to the two-tier structure of CCFT, we can use DCFFTs in the first tier and SCFFTs in the second tier to reduce the multiplicative complexities as well as the overall complexities.

Example 1: Consider a $(15, 11)$ RS code over $\text{GF}(2^4)$ with a generator polynomial $\prod_{i=0}^3 (x - \alpha^i)$, where α is a root of the primitive polynomial $x^4 + x + 1$. This code can correct up to two errors or four erasures, and hence we need to compute the first four frequency-domain components in the DFT of a received codeword as the syndrome. We can decompose the 15-point DFT as 3×5 CCFT by the prime-factor algorithm as shown in Fig. 1. The 3-point SCFFT in the first tier is given by

$$\begin{bmatrix} F_0^{(3)} \\ F_1^{(3)} \\ F_2^{(3)} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \begin{pmatrix} \alpha^0 \\ \alpha^5 \\ \alpha^0 \\ \alpha^0 \end{pmatrix} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} f_0^{(3)} \\ f_1^{(3)} \\ f_2^{(3)} \end{bmatrix},$$

and the 5-point DCFFT in the second tier is given by

$$\begin{bmatrix} F_0^{(5)} \\ F_1^{(5)} \\ F_2^{(5)} \\ F_3^{(5)} \\ F_4^{(5)} \end{bmatrix} = \begin{bmatrix} 1000000001 \\ 1111100000 \\ 1110000111 \\ 1110011110 \\ 1111111000 \end{bmatrix} \begin{pmatrix} \alpha^0 \\ \alpha^{10} \\ \alpha^9 \\ \alpha^8 \\ \alpha^0 \\ \alpha^{10} \\ \alpha^0 \\ \alpha^4 \\ \alpha^0 \\ \alpha^0 \end{pmatrix} \cdot \begin{bmatrix} 10000 \\ 01100 \\ 01111 \\ 01001 \\ 00100 \\ 01111 \\ 00110 \\ 00110 \\ 00001 \\ 01111 \end{bmatrix} \begin{bmatrix} f_0^{(5)} \\ f_1^{(5)} \\ f_2^{(5)} \\ f_3^{(5)} \\ f_4^{(5)} \end{bmatrix}.$$

Since we need to compute the first four frequency components, from Fig. 1 we need the first and the fourth output from the first 5-point CCFT module, the second output from the second

one, and the third output from the third one. Then the 5-point DFT modules can be simplified by removing the unnecessary computations accordingly. For example, when we simplify the first 5-point DFT module, We can remove the second, third, and fifth rows in $\mathbf{A}\mathbf{Q}$, resulting in the fourth and fifth column containing only zero. Then the corresponding rows in \mathbf{c} and \mathbf{P} can be removed, thus reducing the additive and multiplicative complexities. This is a similar reduction procedure with the partial CCFT. However, the DFT modules in the first tier cannot be simplified because all the outputs of these modules are required for the computation in the second tier.

Example 2: Now let us consider a $(15, 13)$ RS code which can correct one error or up to two erasures. Only the first two frequency-domain components are needed and we still decompose the 15-point DFT by the prime-factor algorithm as 3×5 CCFT. From Fig 1, no output from the third 5-point DFT module is needed and hence it can be removed. Therefore, the last output from each 3-point DFT modules in the first tier is not needed, and hence they can be simplified by removing unnecessary computations accordingly. Only in this kind of cases, i.e., the number of the required frequency-domain components is less than the number of DFTs in the second tier, the computational complexity of the first tier can be reduced.

Example 3: Consider a $(10, 6)$ RS code shortened from a $(15, 11)$ code. In the syndrome computation step, we still need four frequency components, which implies the 5-point DFTs in the second tier can be simplified in the same way with Example 1. Moreover, as the input $f_{10}, f_{11}, \dots, f_{14}$ are zero, the 3-point DFT modules in the first tier connecting to these inputs can be accordingly simplified.

These examples are relatively small, and they do not have smaller complexities than the corresponding partial CCFTs. However, we can expect that the partial CCFT will have smaller computational complexity as the length of RS code increase.

B. Syndrome Computation

For an (n, k) RS code, the syndromes of a received vector $\mathbf{r} = (r_0, r_1, \dots, r_{n-1})^T$ are given by $S_j = \sum_{i=0}^{n-1} r_i \alpha^{ij}$ for $0 \leq j \leq 2t - 1$, which are the first $2t$ frequency domain elements of the DFT of \mathbf{r} and can be computed with our partial CCFT. For an (n', k') RS codes shortened from the (n, k) codes, we can still use the n -point partial CCFT to compute the syndrome, provided that the time-domain elements of the CCFT input with indexes $i \geq n'$ are set to zero. The partial CCFT can be then simplified correspondingly by removing the unnecessary computations.

Due to their widespread applications, we select the $(255, 223)$, $(511, 447)$, and $(1023, 895)$ RS codes over $\text{GF}(2^8)$, $\text{GF}(2^9)$, and $\text{GF}(2^{10})$, respectively, as examples to show computational complexity reduction by partial CCFTs. We also select two shortened RS codes with parameters $(2720, 2550)$ [2] and $(3073, 2731)$ [3] over $\text{GF}(2^{12})$ to illustrate the advantage of the two-tier structure.

We compare the complexities of syndrome computation for the five RS codes mentioned above based on partial CCFTs,

partial SCFFT, prime-factor algorithm [14], and Horner's rule [1] in Tab. I. For partial CCFTs, we have tried all possible decompositions of the DFT lengths, and only the non-trivial decompositions with the smallest computational complexities are listed in Tab. I. Note that due to the extreme code length, the additive complexities of the syndrome computation for the two shortened RS codes over $\text{GF}(2^{12})$ based on partial CCFTs are not optimized with the CSE algorithm in [10]. The total complexity in Tab. I is defined to be a weighted sum of the additive and multiplicative complexities. We assume that one multiplication has the same complexity as $(2m - 1)$ additions over the same field. This assumption comes from both the hardware and software considerations [10]. In Tab. I, the smallest total complexities for all the codes are in boldface.

From Tab. I, we can see that both partial CCFTs and partial SCFFT have much smaller complexities than the Horner's rule, which is used widely in practice. In $\text{GF}(2^8)$, partial CCFT have a higher multiplicative complexity than partial SCFFT. However, due to the reduced additive complexities, partial CCFTs have advantages in smaller overall computational complexities in $\text{GF}(2^m)$ when $m = 9$ or 10 , although the improvement is marginal in $\text{GF}(2^9)$ and $\text{GF}(2^{10})$, roughly 1% and 4%, respectively. Due to the sub-optimality of the CCFT and the efficiency of the CCFT for long DFTs, the savings will be greater for larger fields. For the two shortened RS codes over $\text{GF}(2^{12})$, the total complexities based on partial CCFTs are only a **fraction** of those based on partial CCFTs.

C. Chien Search and Error Magnitude Evaluation

In RS decoders, the Chien search is used to determine the error (errata) locations by finding the roots of the error (errata) locator polynomial $\Lambda(x)$. It is implemented by evaluating $\Lambda(x)$ at all points α^i in the finite fields $\text{GF}(2^m)$ with $0 \leq i \leq 2^m - 2$, which can be done efficiently by fast DFT algorithms such as partial CCFT in our paper. The input vector of the DFT only has at most $2t + 1$ nonzero elements. For shortened (n', k') RS codes, possible error (errata) locations must be less than n' . Therefore, only the first n' frequency-domain components are needed, and hence partial CCFT can be simplified accordingly.

For the RS codes we study, Forney's formula [1] is given by $Y_i = -\frac{\Omega(x)}{x\Lambda'(x)} \Big|_{x=\alpha^{-j}}$, where Y_i is the error (errata) magnitude at the i -th error (errata) located at position j , and $\Lambda'(x)$ is the formal derivative of $\Lambda(x)$. Although we evaluate $\Omega(x)$ and $\Lambda(x)$ only at the points corresponding to the error locations, the error locations are variable from one received vector to another. Therefore, we can evaluate $\Omega(x)$ and $\Lambda'(x)$ at all the points in the finite field using partial CCFT, and then select the frequency-domain components corresponding to the error locations.

Moreover, we can combine the computation of the Chien search and Forney's formula by splitting the polynomial $\Lambda(x)$ into $\Lambda_e(x) + \Lambda_o(x)$, where $\Lambda_e(x)$ and $\Lambda_o(x)$ are the sums of the terms in $\Lambda(x)$ with even and odd degrees, respectively. It is easy to verify that in $\text{GF}(2^m)$, $x\Lambda'(x) = \Lambda_o(x)$. Hence we can first evaluate the three polynomials $\Omega(x)$, $\Lambda_e(x)$, and $\Lambda_o(x)$ at all points in the finite field by partial CCFT, and then compute $\Lambda(a)$ by $\Lambda_e(a) + \Lambda_o(a)$ for all $a \in \text{GF}(2^m)$ with n additional

TABLE I
COMPLEXITY COMPARISON OF THE SYNDROME COMPUTATION FOR ERRORS-AND-ERASURES RS DECODERS.

Field	code	Partial CCFT				Partial SCFFT [7]			Prime-factor [14]			Horner's rule [1]	
		$n_1 \times n_2$	Mult.	Add.	Total	Mult.	Add.	Total	Mult.	Add.	Total	Mult.	Add.
GF(2 ⁸)	(255, 223)	3 × 85	252	2652	6432	149	3970	6205	852	1804	14584	7874	8128
GF(2 ⁹)	(511, 447)	7 × 73	873	7268	22109	345	16471	22336	5265	7309	35496	32130	32640
GF(2 ¹⁰)	(1023, 895)	31 × 33	2868	18569	73061	824	60471	76397	6785	15775	144690	129794	130816
GF(2 ¹²)	(2720, 2550)	63 × 65	7565	63869	237864	1467	1244779	1278520	–	–	–	459511	462230
GF(2 ¹²)	(3073, 2731)	63 × 65	9268	82684	295848	2782	2760210	2824196	–	–	–	1047552	1050624

TABLE II
COMPLEXITY COMPARISON OF COMBINED CHIEN SEARCH AND FORNEY'S FORMULA FOR ERRORS-AND-ERASURES RS DECODERS.

Field	code		Partial CCFT					Partial DCFFT				Horner's Rule [1]			
			$n_1 \times n_2$	Mult.	Add.	Div.	Total	Mult.	Add.	Div.	Total	Mult.	Add.	Div.	Total
GF(2 ⁸)	(255, 223)	$\Omega(x)$	85×3	252	2764	0	6544	149	3226	0	5461	992	992	0	15872
		$\Lambda_e(x)$	85×3	177	1845	0	4500	78	1828	0	2998	4064	4080	0	65040
		$\Lambda_o(x)$	85×3	191	2230	0	5095	108	3096	0	4716	4064	3825	0	64785
		Misc		0	255	32		0	255	32		0	255	32	
		Total						13175 + 32 divisions					145952 + 32 divisions		
GF(2 ⁹)	(511, 447)	$\Omega(x)$	73×7	834	6013	0	20191	345	12791	0	18656	4032	4032	0	72576
		$\Lambda_e(x)$	73×7	658	4353	0	15539	177	7802	0	10811	16320	16352	0	293792
		$\Lambda_o(x)$	73×7	678	4684	0	16210	248	12533	0	16749	16320	15841	0	293281
		Misc		0	511	64		0	511	64		0	511	64	
		Total						46188 + 64 divisions					660160 + 64 divisions		
GF(2 ¹⁰)	(1023, 895)	$\Omega(x)$	33×31	2687	16743	0	67796	824	52557	0	68213	16256	16256	0	325120
		$\Lambda_e(x)$	33×31	2295	14718	0	58323	430	30294	0	38464	65408	65472	0	1308224
		$\Lambda_o(x)$	33×31	2291	14523	0	58052	541	51655	0	61934	65408	64449	0	1307201
		Misc		0	1023	128		0	1023	128		0	1023	128	
		Total						165335 + 128 divisions					2941568 + 128 divisions		
GF(2 ¹²)	(2720, 2550)	$\Omega(x)$	65×63	7807	65253	0	244814	1542	1326289	0	1361755	28730	28730	0	689520
		$\Lambda_e(x)$	65×63	6889	57631	0	216078	787	691858	0	709959	231115	231200	0	5546845
		$\Lambda_o(x)$	65×63	6897	57095	0	215726	1082	1320622	0	1345508	231115	228480	0	5544125
		Misc		0	2720	170		0	2720	170		0	2720	170	
		Total						679338 + 170 divisions					11780490+170 divisions		
GF(2 ¹²)	(3073, 2731)	$\Omega(x)$	65×63	9610	77852	0	298882	2908	2760306	0	2827190	116622	116622	0	2798928
		$\Lambda_e(x)$	65×63	8033	66641	0	251400	1550	1497544	0	1533194	525312	525483	0	12607659
		$\Lambda_o(x)$	65×63	8018	65968	0	250382	2041	2751557	0	2798500	525312	522410	0	12604586
		Misc		0	3073	342		0	3073	342		0	3073	342	
		Total						803737 + 342 divisions					28014246 + 342 divisions		

additions. The error locations are the points where $\Lambda(x) = 0$. With Forney's formula, the error (errata) magnitudes can be computed with at most t divisions ($2t$ divisions).

In Tab. II, we compare the computational complexity of combined Chien search and Forney's formula based on partial CCFTs with non-trivial decompositions, partial DCFFTs, and Horner's rule for the five RS codes and shortened RS codes discussed in Sec. III-B. The choices of partial CCFTs and CFFTs do not affect the number of divisions. Similar to syndrome computation, the advantage of using partial CCFTs (with non-trivial decompositions) instead of partial CFFTs is rather limited for RS codes over GF(2 ^{m}) when $m \leq 10$. However, the advantage of partial CCFTs is much greater in larger fields. Again for the two shortened RS codes over GF(2¹²), the total complexities based on partial CCFTs are only a **fraction** of those based on partial CFFTs. Finally, since partial CFFTs are special cases of partial CCFTs with trivial decomposition, we can choose the most efficient algorithm to evaluate $\Omega(x)$, $\Lambda_e(x)$, and $\Lambda_o(x)$, respectively. In Tab. II, the total complexity of combined Chien search and Forney's formula based on partial CCFTs/CFFTs is also provided.

IV. HARDWARE IMPLEMENTATIONS

The additive and multiplicative complexities derived in Sec. III considers only the total number of the additions and multiplications required by partial CCFTs. Although this metric is a good estimation of the computational complexities, it reflects only part of the hardware complexities. For example, buffers, multiplexers and control units are required if we want to reuse modules to save chip area, and their complexities need to be accounted for. Thus, in this section hardware implementations are used to further verify and demonstrate the advantages of partial CCFTs.

In the literature, numerous syndrome-based RS decoder designs use the Horner's rule [1] to implement the syndrome computation, Chien search, and Forney's formula. Since we want to replace the Horner's rule by partial CCFT, the syndrome computation module is representative to illustrate the advantages of the partial CCFT. Although the architecture and hardware design of RS decoders are well-studied in the literature, there are few results on the RS codes over GF(2¹²) due to their extreme lengths. Therefore, in this section, we choose to implement in hardware the syndrome computation block for the (2720, 2550) shortened RS code in [2] as an example, because detailed synthesis results of the syndrome computation block are provided in [2]. Two

VLSI designs synthesized with 0.18 μm CMOS technology are provided in [2] with different parallelization parameters. We also implement this block with partial CCFTs, and synthesize it with a more advanced 45 nm technology [15]. No hardware implementation results is provided in [7]. Given the extreme length of this code, since the CSE algorithm cannot be used to reduce additive complexities of partial CFFT, partial CCFTs have a significant advantage against partial CFFTs, as shown in Tabs. I and II.

A. Hardware Implementations

When we use partial CCFTs to compute the syndrome for the (2720, 2550) RS code, 2720 time-domain elements and 170 frequency-domain components are needed in the 4095-point DFT. If we implement this block in a fully parallel fashion, the computational complexity in Tab. I is a good estimate of the hardware complexity. However, the hardware complexity is too large to be used in practice. Fortunately, the modular structure of partial CCFTs enables us to fold the architecture. Since the CCFTs decompose the long DFTs into several short sub-DFTs, those sub-DFTs can be used as modules in hardware implementations. They can be reused to save the chip area and power consumption, or pipelined and parallelized to increase the throughput. This is a desirable property in hardware implementation of the RS decoders.

In our hardware implementation, we first decompose the 4095-point DFT as 63×65 as suggested by Tab. I, i.e., first compute 65 63-point DFTs and then compute 63 65-point DFTs. To compute these DFTs in one clock cycle in a fully parallel way, it requires 65 63-point DFT modules and 63 65-point DFT modules. This straightforward implementation has very high complexity. Instead, we carry out the partial CCFT in two steps. The first step computes the 65 63-point DFTs in T_1 clock cycles, each cycle computing at most $\lceil 65/T_1 \rceil$ 63-point DFTs; and the second step computes the 63-point DFTs in T_2 clock cycles, each cycle computing at most $\lceil 63/T_2 \rceil$ 65-point DFTs. Therefore, we can compute the partial CCFT in $T_1 + T_2$ cycles with $\lceil 65/T_1 \rceil$ 63-point DFT modules and $\lceil 63/T_2 \rceil$ 65-point DFT modules. These 63-point DFT modules and 65-point DFT modules are implemented by CFFTs to reduce their complexities, and the computations involving the zero time-domain inputs and/or unnecessary frequency-domain components are removed.

B. Implementation Results and Remarks

We provide two hardware designs with (T_1, T_2) equal to (13, 9) and (5, 7), respectively. The synthesis results are shown in Tab. III, and they are compared with the two designs with different parallelization parameters in [2]. Due to the different process technologies used in the synthesis, the clock rates can not be compared directly. We provide both clock rates as well as throughputs of all implementations (the throughput is defined as the number of vectors that can be processed in each second). The equivalent gate count is computed by dividing the total chip area by the area of an XOR gate in the corresponding technology, and it can serve as a metric to compare designs in different process technologies.

TABLE III
COMPARISON OF THE VLSI IMPLEMENTATIONS OF THE SYNDROME COMPUTATION FOR (2720, 2550) RS CODE.

(T_1, T_2)	Partial CCFT		Honer's Rule [2]	
	(5, 7)	(13, 9)		
Process	45 nm	45 nm	0.18 μm	0.18 μm
Clock rate	250 MHz	200 MHz	112 MHz	225 MHz
Gate count	384k	306k	920k	480k
Require cycles	12	22	86	171
Throughput (vec/s)	20.8M	9.1M	1.3M	1.3M

From Tab. III, we can see that both the gate count and required cycles are reduced greatly compared with the designs in [2] because a partial CCFT has a much smaller computational complexity than Horner's rule. With partial CCFTs, we can design an RS decoder with smaller area and larger throughput because of reduced gate counts and required numbers of cycles, respectively.

Due to the modular structure of partial CCFTs, we can make a wide range of trade-offs between the chip area and throughput. We can reduce the number of the required cycles by increasing the number of sub-DFT modules in each tier, and the chip area is therefore increased. For example, if we reduce the required cycles from 22 to 12, the gate count increases from 306k to 384k as shown in Tab. III. In contrast, it is not easy for partial CFFTs to make such trade-offs because of the irregular structure of the post-addition network for partial CFFTs (see [7]). Moreover, since we compute the sub-DFTs by CFFTs, which are implemented as bilinear algorithms and also have modular structure, we can shorten the critical path and improve the clock rate by pipelining the sub-DFT modules, i.e., inserting pipeline registers between pre-addition network, multipliers, and post-addition network.

We remark that we focus on the decomposition 63×65 for the 4095-point DFT above. Other decompositions, even multi-tier structure decomposition, can be considered. For example, a decomposition $7 \times 9 \times 5 \times 13$ would lead to a four-tier structure, which leads to a smaller critical path delay since the sub-DFTs in each tier are smaller and they can be pipelined.

V. CONCLUSION

We extend our previous work in [11] by proposing partial CCFT to reduce the computational complexity of syndrome based RS decoder. Our results show that partial CCFTs have advantages in reducing the computational complexity of the DFTs, which can be used to implement the syndrome computation, Chien search, and Forney's formula. The hardware implementation results show that since the computational complexity is reduced greatly, smaller chip area and fewer clock cycles are needed to compute the syndrome of the a received vector. Moreover, the modular structure of partial CCFT provides a wide range of trade-offs between the chip area and throughput, which is a favorable property in hardware designs.

REFERENCES

- [1] R. E. Blahut, *Theory and Practice of Error Control Codes*. Addison-Wesley, 1984.

- [2] T. Buerner, R. Dohmen, A. Zottmann, M. Saeger, and A. J. van Wijngaarden, "On a high-speed Reed-Solomon CODEC architecture for 43 Gb/s optical transmission systems," in *Proc. 24th International Conference on Microelectronics*, vol. 2, May 16–19, 2004, pp. 743–746.
- [3] S. Jeon and B.V.K. Vijaya Kumar, "Performance and complexity of 32 k-bit binary ldpc codes for magnetic recording channels," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 2244–2247, 2010.
- [4] Y. Han, W. E. Ryan, and R. Wesel, "Dual-mode decoding of product codes with application to tape storage," in *Proc. IEEE Global Telecommunications Conference*, vol. 3, Nov. 28–Dec. 2, 2005, pp. 1255–1260.
- [5] "Hard disk drive long data sector white paper," April 20 2007. [Online]. Available: <http://www.idema.org/>
- [6] E. Costa, S. V. Fedorenko, and P. V. Trifonov, "On computing the syndrome polynomial in Reed-Solomon decoder," *European Transactions on Telecommunications*, vol. 15, no. 4, pp. 337–342, 2004. [Online]. Available: <http://dx.doi.org/10.1002/ett.982>
- [7] N. Chen and Z. Yan, "Reduced-complexity Reed-Solomon decoders based on cyclotomic FFTs," *IEEE Signal Process. Lett.*, vol. 16, no. 4, pp. 279–282, 2009.
- [8] P. V. Trifonov and S. V. Fedorenko, "A method for fast computation of the Fourier transform over a finite field," *Probl. Inf. Transm.*, vol. 39, no. 3, pp. 231–238, 2003.
- [9] S. V. Fedorenko, "A method for computation of the discrete Fourier transform over a finite fields," *Probl. Inf. Transm.*, vol. 42, pp. 139–151, 2006.
- [10] N. Chen and Z. Yan, "Cyclotomic FFTs with reduced additive complexities based on a novel common subexpression elimination algorithm," *IEEE Trans. Signal Process.*, vol. 57, no. 3, pp. 1010–1020, Mar. 2009.
- [11] X. Wu, M. Wagh, N. Chen, Y. Wang, and Z. Yan, "Composite cyclotomic fourier transforms with reduced complexities," *IEEE Trans. Signal Process.*, vol. 59, no. 5, pp. 2136–2145, 2011.
- [12] I. J. Good, "The interaction algorithm and practical Fourier analysis," *Journal of the Royal Statistical Society. Series B (Methodological)*, vol. 20, no. 2, pp. 361–372, 1958. [Online]. Available: <http://www.jstor.org/stable/2983896>
- [13] J. W. Cooley and J. W. Tukey, "An algorithm for the machine calculation of complex Fourier series," *Mathematics of Computation*, vol. 19, no. 90, pp. 297–301, 1965.
- [14] T. K. Truong, P. D. Chen, L. J. Wang, Y. Chang, and I. S. Reed, "Fast, prime factor, discrete Fourier transform algorithms over $GF(2^m)$ for $8 \leq m \leq 10$," *Inf. Sci.*, vol. 176, no. 1, pp. 1–26, 2006.
- [15] [Online]. Available: <http://vcag.ecen.okstate.edu/projects/scells/>